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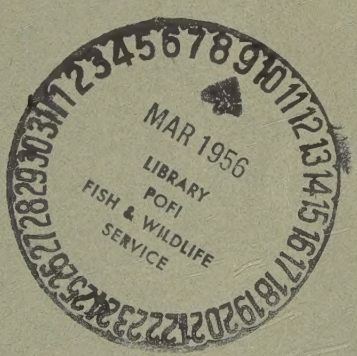

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The Depth of the Wind-Produced Homogeneous Layer in the Oceans

For a number of reasons, practical as well as scientific, it is of interest to have information about the depth of the homogeneous layer as it actually occurs in the oceans. This might perhaps be obtainable from the existing collection of serial observations of temperature and salinity, but examination of these would be a very lengthy task. Undoubtedly the information could best be obtained from bathythermograph records, but not many of them are yet available to everyone, and at the time the present study was begun, there were very few.

The homogeneous layer has been fully discussed from the theoretical side by Rossby and Montgomery (1). They define it as the shallow surface layer which is homogeneous in respect of all its properties, and distinguish it from the more or less uniform layer above the principal thermocline, which may be at a depth of some hundreds of metres. In its steady state, the homogeneous layer must coincide with the turbulent and drift-current layers. The turbulent mixing from which it results is considered to be mainly the effect of the wind. Convection is also a mixing agent, and other sources of turbulence which affect the layer are tidal and other currents by which one body of water is moved over another. For the open ocean in general these latter sources of turbulence are regarded as of secondary importance to the wind in the development of the homogeneous layer.

Time is needed for the layer to reach the steady state appropriate to a given wind. In estimating the depth of the layer as shown by temperature and salinity series, Rossby and Montgomery chose stations at which the wind appeared to have been constant for two days and without material increase for three or four days; they consider that this would be " sufficient time for the homogeneous layer to become established to approximately its normal thickness, even in a moderately stable ocean ". Similarly, Francis and Stommel (2), in their examination of bathythermograph records, compare the conditions prevailing immediately before the onset of a gale with those found three or four days after.

Rossby and Montgomery point out that there seem to be effects tending to dissipate the homogeneous layer. " Otherwise its thickness in any locality would correspond to the highest wind ever present there, whereas usually a few days after a decrease in wind the thickness of the layer is observed to have decreased again." They find this dissipation of the layer difficult to explain, but suggest that it results from turbulence arising at the discontinuity at the foot of the layer, or from the addition of heat at the surface. Apart from this, there does not appear to be much information about the time which elapses in various circumstances before the layer becomes appreciably shallower or before it loses its uniformity to a recognizable degree.

As a matter of experience, except in certain regions, a more or less homogeneous layer is quite often encountered, and one tends to expect to find it, moreover, round about a given depth according to season and locality. Halldal (3), for example, remarks that at Ocean Weather Station M, in the Norwegian Sea, a discontinuity layer was present between 25 and 50m. in May 1949 and that as the summer advanced the depth of this layer gradually increased until breakdown occurred at the end of October. Francis and Stommel's (2) observations show the effect of a gale as deepening an already existing layer, which, before the gale began, was occasionally completely isothermal and usually very nearly so, notwithstanding the calm weather which preceded the gale.

Evidently the fluctuations of the thickness of the layer are not so rapid as to reflect every change in wind strength. It would seem that the combined effects of the agents

which dissipate the layer and of those which develop and maintain it tend to the establishment of a more or less steady state. In other words, it might be expected that the frequency distribution of the layer depth, relative to that of the local wind strength, would be high in the neighbourhood of the median and low towards the extremities. No attempt has yet been made, however, to test this possible relationship.

The wind observations made by ships on behalf of the British Meteorological Office were made available in the form of wind strength frequencies (in Beaufort units, regardless of direction) for each month and for each Marsden Square (10° of latitude by 10° of longitude) for latitudes below 60°. These observations refer, of course, to some (not always the same) height above sea level, but no attempt to adjust them has been made. In order to obtain an idea of the range of depths most likely to be encountered, the statistics chosen to represent these data were the first and third quartiles. These were estimated for each month, and averaged by three-monthly periods.

Rossby and Montgomery (1) express the depth, h, of the homogeneous layer as a function of the wind speed as follows:

$$h = K.\text{cosec } L.W_0 - K'.\ W_0^2,$$

where L is the latitude, and W_0 the wind speed at the level of the sea surface. In consideration of the uncertainties involved, the second-order term has been discarded in the present study; this amounts in effect to including the boundary layer at the foot of the wind-stirred layer. The coefficient K is a combination of a number of constants. Its value was estimated by Rossby and Montgomery from observations at 39 very carefully selected stations. Only stations were used " for which the wind speed was apparently constant for two days, and where it had not materially exceeded this steady value for three or four days preceding the station ". The depth, h, was taken as the depth of the isothermal layer, as judged by the absence of temperature gradients in excess of 0.01°C. per metre. Stations at which instability occurred were not used. The average of the values found for K is 2.38 sec., with a probable error of ± 0.08. As is pointed out, K should be independent of both W_0 and L, and the authors conclude that K is not correlated with W_0, but that as latitudes as low as about 20° are approached, a latitude effect begins to appear. There is also evidence of a seasonal effect, the value of K showing a sharp drop from almost 3 in mid-winter to about 2 in spring, with a gradual rise thereafter. " The high values in winter ", the authors state, " are of course due to the small amount of stability accompanying the almost isothermal vertical state of the ocean." They conclude that as nearly as can be determined from the observations their formula " is a true representation of the thickness of the homogeneous layer in a reasonably steady state for latitudes greater than 20°, except that perhaps a small allowance must be made for stability ".

TABLE 1.

Values of K Employed for Different Latitudes and Different Seasons.

Lat.°	Winter	Spring	Summer	Autumn
5	1.00	1.00	1.00	1.00
15	2.15	1.80	1.80	2.00
25	2.65	2.05	2.05	2.50
35	2.90	2.15	2.15	2.65
45	3.00	2.20	2.20	2.70
55	3.10	2.25	2.25	2.80

For the present study, values of K appropriate to the middle latitudes of the Marsden Square belts were estimated from the observed values tabulated by Rossby and Montgomery. As these include values for stations in latitudes between 15° and 20°, values of K were estimated for Marsden Squares between 10° and 20°. In order to complete the picture—but, it must be admitted with very little other justification—values were estimated by extrapolation for Marsden Squares between 0° and 10° also, the value at the equator

FIG. 1. Thickness (m.) of the wind-produced homogeneous layer in January-March (estimated from

eneous layer in April-June (estimated from the third quartiles of the wind speed frequencies).

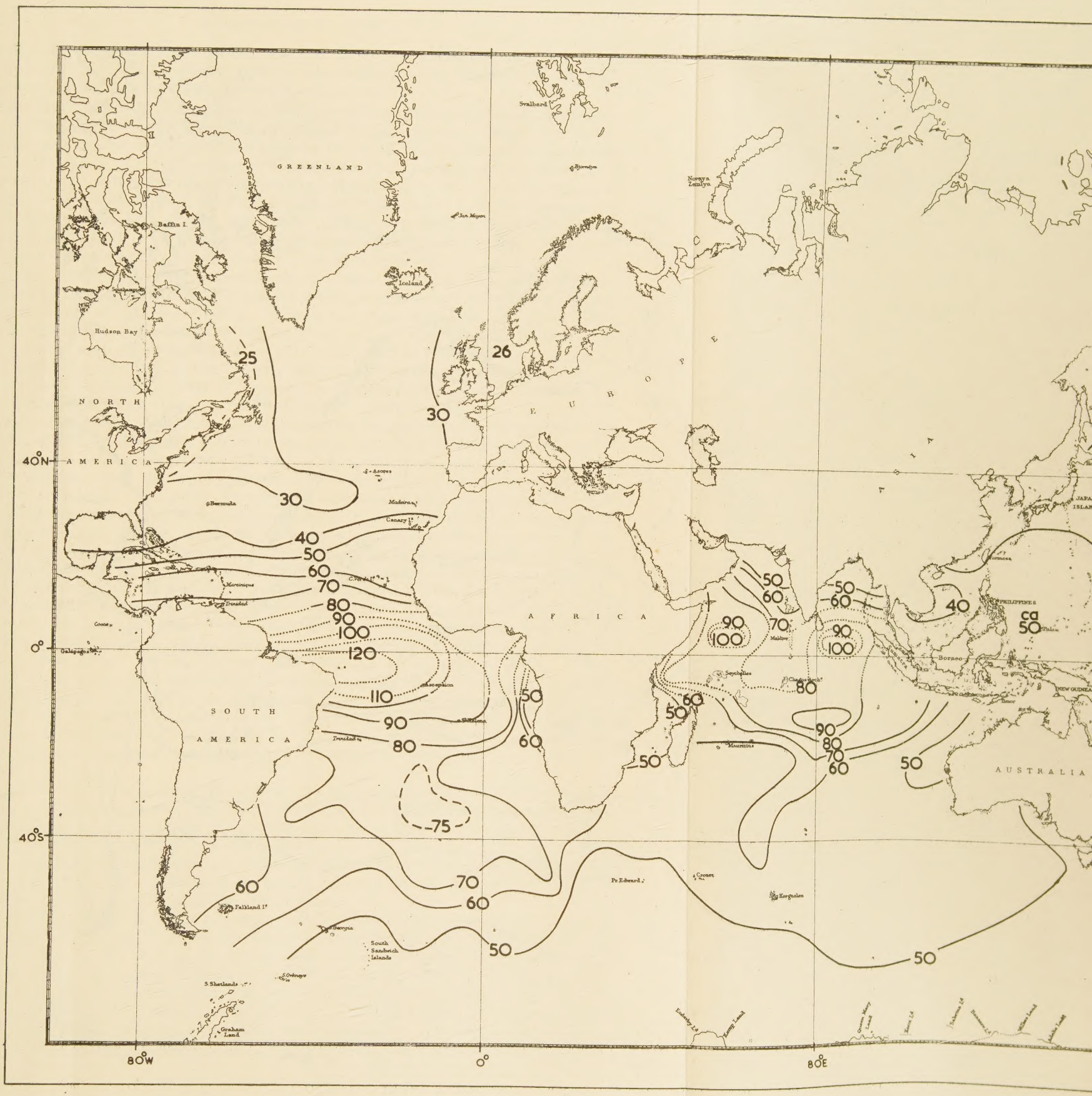
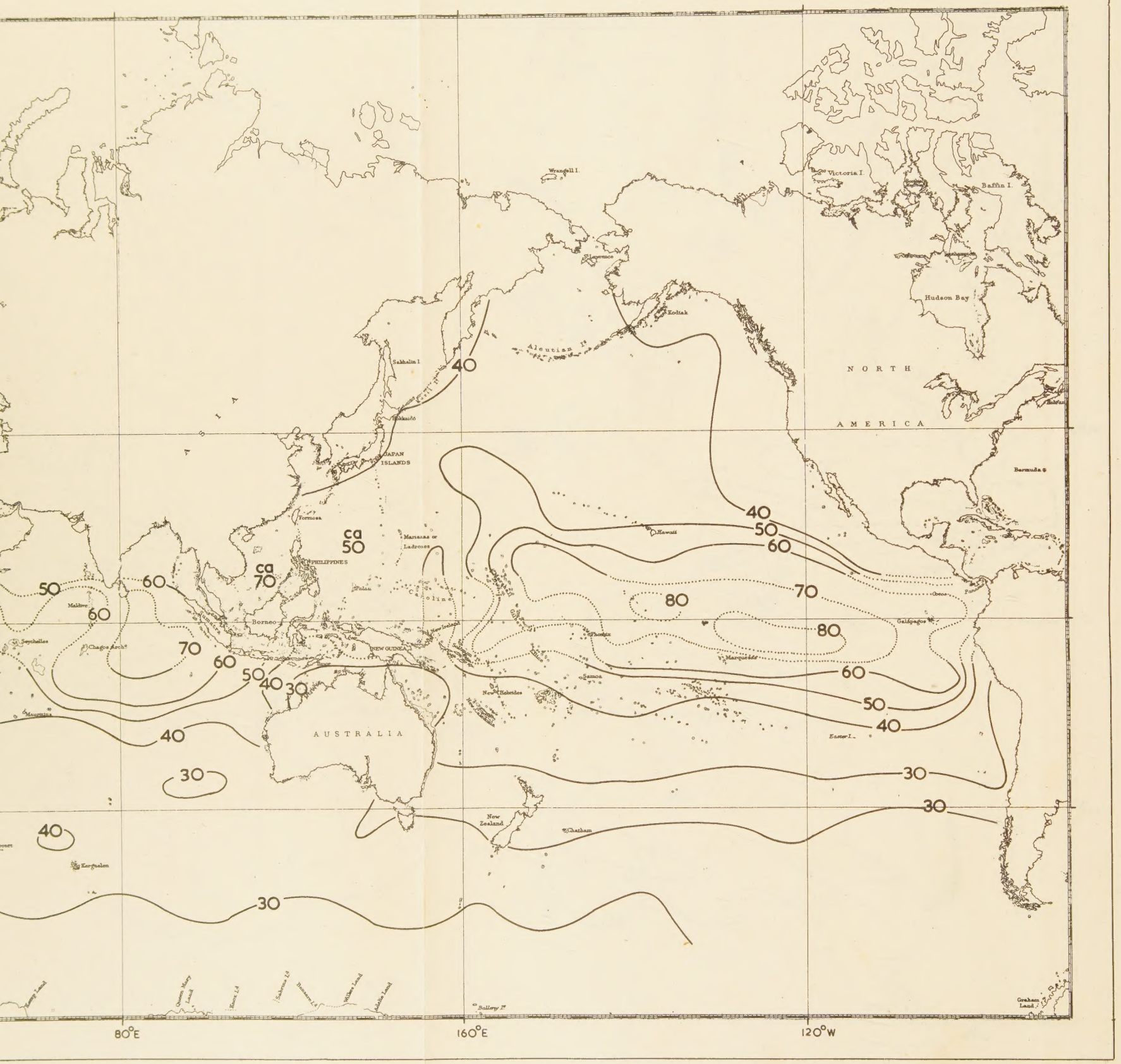


FIG. 3. Thickness (m.) of the wind-produced homogeneous layer in July-September (estimated from the t



homogeneous layer in October-December (estimated from the third quartiles of the wind speed frequencies).

being taken as 0. A latitude effect and a seasonal effect were thus introduced. The values used are shown in Table 1. Winter refers to the months January-March in the northern hemisphere, July-September in the southern; and so on.

With these coefficients and the first and third quartiles of the wind strength frequencies, values of the depth h were computed for each Marsden Square. Originally the two quartiles were chosen as statistics to represent the wind strength in preference to the median, for instance, in order to indicate the range of h, but the first-quartile wind strengths were found to be well below Force 4 almost everywhere, and in view of the uncertainty of the effect of the wind at such low speeds, only the depths relating to the third-quartile wind strengths have been further considered. These have been charted and roughly contoured, as referring to the centre point of the appropriate Marsden Square. The results are shown for three-monthly periods (not for seasons) in Figs. 1-4.

It is not the purpose of the present study to attempt an assessment of the validity of the theory by comparison of computed values of the layer thickness with observed values; indeed, it would be pointless to do so, because numerical expression was given to the theory in the first place by means of very carefully selected observations. In some parts of the sea, the depth of the homogeneous layer is governed to a relatively large extent by factors other than the wind, and as the only effect at present taken into account is that of the wind, the charted depths may be expected to disagree with the conditions prevailing in the localities in which these, normally secondary, effects predominate. But since in general the wind is taken to be the principal cause of the homogeneous layer, the distribution of depths shown by the charts may be expected to accord in a broad way with actual conditions.

With uniform winds, the depth contours of the layer would, of course, be parallel with the circles of latitude. The charts show that the variations in wind strength lead in fact to considerable departure from this zonal distribution. This is most marked in the Atlantic, especially the North Atlantic, where the contours in middle latitudes clearly tend to run meridianally. Evidently the diminution of the effect of the wind with latitude is here more than balanced by the increase in wind strength. In the equatorial Atlantic, the boundary surface at the foot of the layer is shown to deepen considerably from east to west, which is in agreement with Defant's (4) chart of the thickness of the isothermal layer in this locality. The depths also agree in order of magnitude, though on the eastern side, especially, the computed depths are rather greater than Defant's; in the Gulf of Guinea, Defant gives depths of about 25 m., whereas the computed values are of the order of 70 m. This is evidently a case in which the depth to which the wind can mix the surface layers is restricted by the high degree of stability in the upper levels. The regions of maximal layer thickness (over 100 m.) are shown by Defant to lie in mid-ocean in latitudes 20°-30° N. and S. (apart from a small area off C. St. Roque), but the present charts give no indication of this feature, and show maximal depths towards the western side of the ocean in about latitudes 5°N. and S.

It is noticeable that, latitude for latitude, the thickness of the layer in the Atlantic tends to be appreciably greater than that in the Indian and Pacific Oceans, though in July and September, the season of the South-West Monsoon, a layer thicker than 100 m. may evidently be found in limited areas of the Indian Ocean. It is also notable that this contrast between conditions in the Atlantic and in the Indian and Pacific Oceans is reflected in the Southern Ocean as well. Wind data are scanty, however, in the highest latitude belt in the Indian and Pacific sectors of the Southern Ocean.

A detailed examination of the occurrence of the homogeneous layer has been made in two localities, the northern part of the North Sea and that part of Marsden Square 182 (50°-60°N. lat., 10°-20°W. long., on the eastern side of the Atlantic, west of the British Islands) in which the bottom depth exceeds 1,000 m. In the central part of the northern North Sea, during the summer half of the year, the water is divided fairly sharply into two layers, both of which are usually homogeneous. The layers differ at times by nearly 10°C. in temperature, but are as a rule the same in salinity. The data available for the whole region in which the thermocline is usually present (see Fig. 5) are very numerous

and those selected for examination are from two parts of the region. These two parts are also shown in Fig. 5 and are referred to, for convenience, as areas 9E and 12G.

In a paper* read at the meeting of the International Council for the Exploration of the Sea in Copenhagen in October 1953, Dietrich has explained the way in which the two homogeneous layers arise. The upper layer is formed by wind-induced turbulence and the lower one by the turbulence arising from the gradient in the tidal stream speeds set up by friction against the sea bottom. If the ranges of these two effects were to overlap, complete

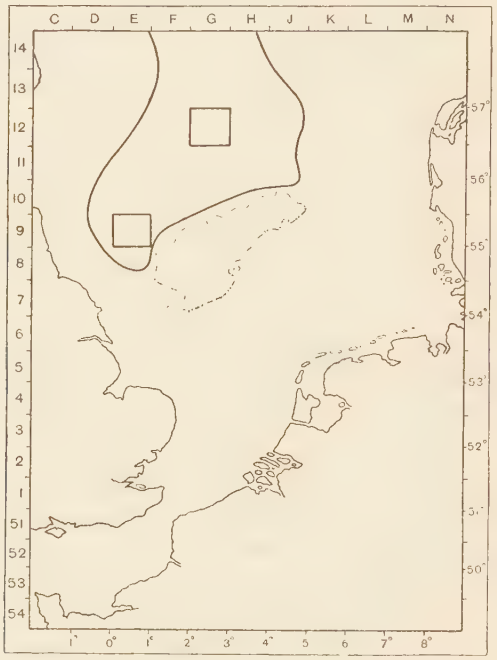


FIG. 5. Region of the North Sea in which a thermocline is usually present in summer. The squares are the localities for which the thickness of the surface homogeneous layer is shown in Fig. 6.

overturn would occur and the characteristic layering would disappear. In the summer season this overlap evidently occurs very seldom or not at all in the central part of the northern North Sea, and the sharpness of the division between the two layers greatly facilitates the estimation of the thickness of the upper, wind-stirred layer. To do this, temperature was plotted against depth, and the depth of the upper homogeneous layer taken as the point at which the curve first showed an appreciable change from a straight line. In most cases the temperature gradient throughout the layer was considerably less than 0.01°C. per metre. These estimates are plotted against date in Fig. 6, for the months May to November (during the winter period the whole water column is uniform). The dots refer to area 12G and the circles to area 9E. The continuous curve was drawn free-hand, by eye, to indicate the general trend of the values estimated from temperature observations, and the pecked curve was drawn from values computed with the formula stated above.

A similar procedure was followed for Marsden Square 182, but as the data are not so numerous, all available for the whole Square (in depths of 1,000 m. or more) were examined. The results are shown in Fig. 7. The dots in this diagram indicate the depths of what may be termed 'old' layers; that is, when examination showed that a slight gradient had formed in the most superficial levels or when there was evidence of double

* Entitled "Die sommerliche Sprungschicht in der mittleren Nordsee und ihr Verhalten auf Grund neuerer Untersuchungen mit 'Gauss'".

layering. Since examples of these conditions were fairly numerous, it was thought worth while to record them. It should also be mentioned that, as in the North Sea region, in Marsden Square 182 there is as a rule very little difference in the salinity of the water column through the range of depths considered. Moreover, the region is not regarded as characterized by strong currents or other conditions which might modify the effect of the wind in stirring the upper layers, though, as is suggested below, the effect of currents may not be entirely negligible.

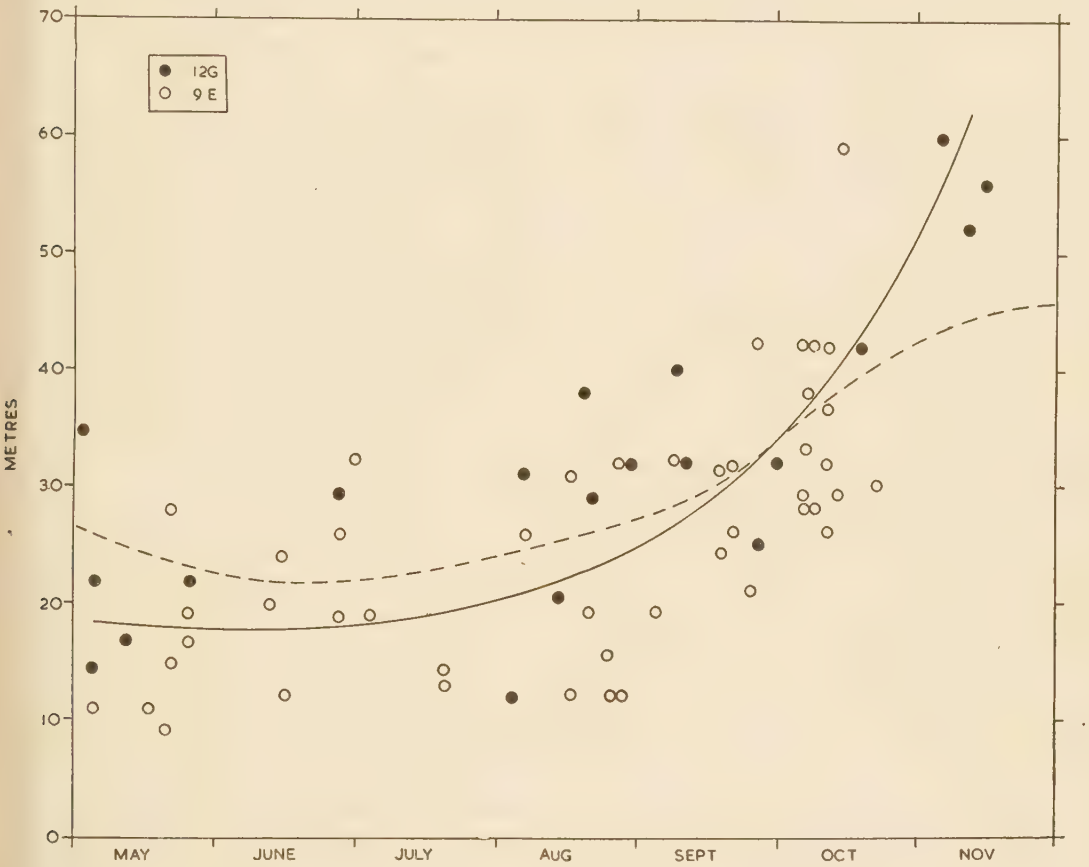


FIG. 6. The thickness of the surface homogeneous layer in two localities in the northern North Sea. The continuous curve relates to observed values; the pecked curve is based on computed values. Dots refer to area 12G, circles to 9E.

The two diagrams exhibit the same general trend in the thickness of the layer. There may be at first, until the end of June, a slight decrease, clearly attributable to the less frequent occurrence of the stronger winds. Until about September the observed values tend to be rather less than the calculated, as may be expected, since they are related to the higher wind strengths. From September onwards, however, the observed increase in thickness is a good deal more rapid than is to be expected from the computed values. This increase in thickness is certainly attributable in part to the increase in the occurrence of stronger winds, and in part, at least towards the end of the period, to loss in stability of the water column. The difference between the observed and computed values is rather wider, however, than these two effects alone would seem to account for. The layer is two or three times as thick in November as in May, for instance, and it would therefore seem that there must be sources of turbulence besides the wind which appreciably influence the thickness of the layer in autumn.

The average hydrographic conditions, season by season, are shown in Table 2 for a

part of Marsden Square 182. The area covered by the whole Square being rather large, the variance of temperature due to geographical position was considerable, which resulted in a somewhat irregular picture of seasonal change. A group of stations was found, however, in the area 50°-52°N. and 10°-14°W., which seemed suitable, but these also showed irregularities, which appeared to be due to variance between years. Averages were therefore estimated from the data for the earlier years, 1905-1914, and these are given in Table 2. The stability values are rough approximations only, having been estimated from

$$\frac{\Delta\sigma_t}{\Delta z} \cdot 10^5 *$$

This table indicates that in the Atlantic region the distribution of stability in the water column in November differs from that in May, for instance, in that in May the surface homogeneous layer is developing in a water column with high stability in the uppermost levels, whereas in November the homogeneous layer is already present and stability is accordingly low in these levels. The effect of high winds in deepening the layer may therefore be somewhat greater in November than in May.

Another process in which a possible explanation may be sought for the difference in the layer thickness at these two seasons is convection. In autumn, heat is in general being

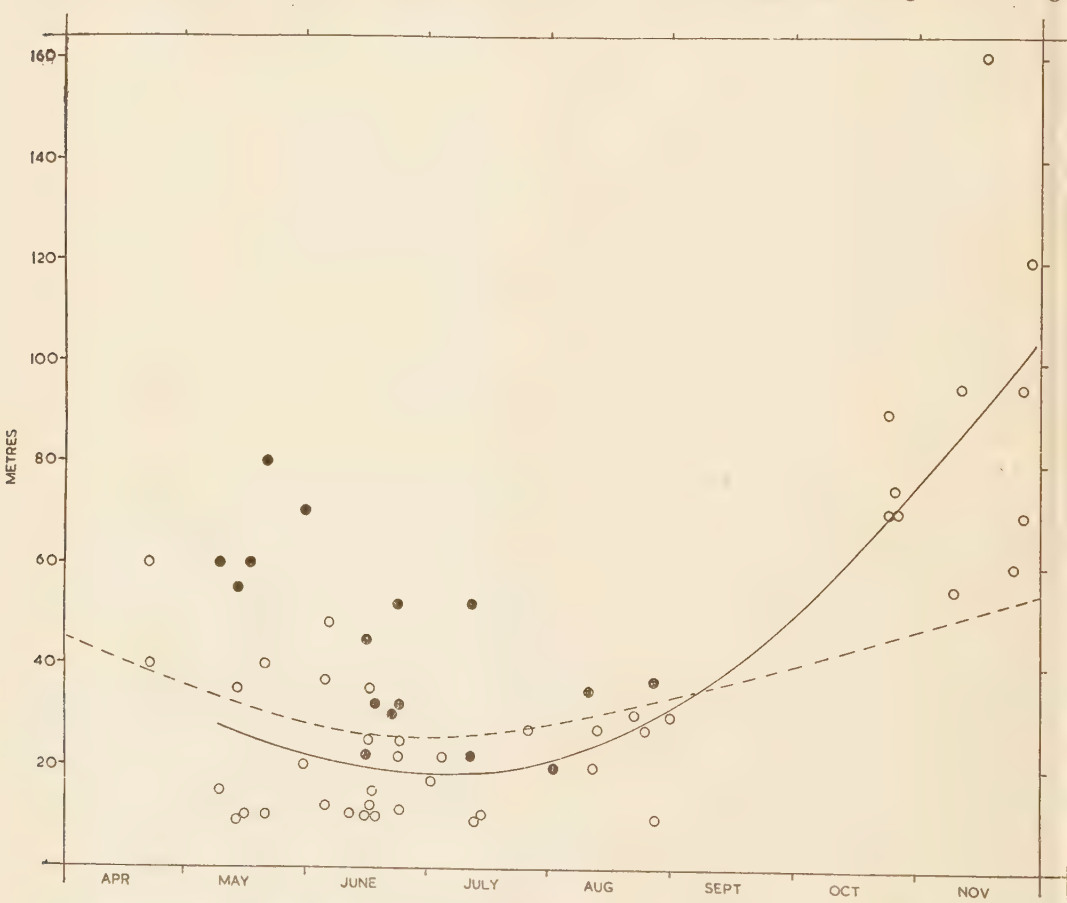


FIG. 7. The thickness of the surface homogeneous layer in water 1,000 m. or more deep in Marsden Square 182 (eastern North Atlantic). The continuous curve relates to observed values; the pecked curve is based on computed values. Dots refer to ' old ' layers (incomplete homogeneity), circles to completely homogeneous layers.

* See Sverdrup, Johnson, and Fleming (5), p. 417.

lost from the surface levels, whereas in spring the trend is towards gain. In both May and November, however, there is very little difference between the average temperature of the sea surface and that of the air, at least in the Atlantic. The minimal sea surface temperatures* in both months are about 10°C., which with a salinity of 35.45°/₀₀ gives a value of σ_t of 27.32. Surface water cooled to this extent would be more unstable at 100 or 200 m. in November than in May. Or, to put it in another way, in order to produce surface water which would be in neutral equilibrium at 100 or 200 m., the water would not require to reach so low a temperature in November as in May, and the likelihood of convective processes playing a part in deepening the homogeneous layer is therefore greater in November.

TABLE 2.

Monthly Means of Temperature and Salinity over the Period 1905-1914 at Stations with a Bottom Depth of 1,000 m. or over within the area 50°-52°N., 10°-14°W. (Part of Marsden Square 182).

Metres		0 m.	50	100	200	400
Feb. (5 Stas.)	t°C.	10.41	10.32	10.32	10.31	10.26
	S°/₀₀	35.40	35.34	35.34	35.34	35.34
	σ_t	27.21	27.18	27.18	27.18	27.19
	Stability		−60	0	0	
May (10 Stas.)	t°C.	11.73	10.61	10.57	10.40	10.20
	S°/₀₀	35.45	35.44	35.44	35.46	35.43
	σ_t	27.01	27.21	27.21	27.26	27.27
	Stability		400	0	50	
Aug. (13 Stas.)	t°C.	16.31	12.75	10.91	10.39	10.17
	S°/₀₀	35.42	35.44	35.46	35.46	35.44
	σ_t	26.02	26.80	27.17	27.26	27.28
	Stability		1560	740	90	
Nov. (5 Stas.)	t°C.	12.16	12.07	11.78	10.82	10.39
	S°/₀₀	35.45	35.44	35.44	35.46	35.44
	σ_t	26.91	26.93	26.99	27.18	27.24
	Stability		40	120	190	

The reason for this is to be found in the increase in temperatures which occurs in the deeper levels in autumn. Convective processes can have little to do with this occurrence, since they could lead to higher temperatures at deeper levels only if the surface cooling were accompanied by an increase in salinity. In the region under consideration the salinity rise in autumn is barely appreciable, so far as the data used show.

The retardation of phase with increasing depth and the diminution of amplitude in the seasonal temperature cycle are well known. Sverdrup, Johnson, and Fleming (5) discuss this phenomenon, the process concerned being eddy conductivity. They conclude that " below a depth of 300 m. the temperature of the ocean is not subject to any annual variation ", and quote an example for a position in the Bay of Biscay (47°N., 12°W. approx.) in which the range at 100 m. is given (after Fjelstad) as 0.46°C. Table 2 above indicates that in this particular part of Marsden Square 182, the range at 100 m. is 1.46°C.; that at 200 m. is 0.51°, and at 400 m., 0.22°C. Accordingly, it appears that in this case the rise in temperature in the deeper levels in autumn must be due to advection, in part, if not entirely. The form of the annual curves, it is thought, also supports this view; at 400 m. the whole range is covered between August and November (Fig. 8). It is therefore suggested that in this particular region the additional turbulence from which springs the unexpectedly great depth of the homogeneous layer in autumn must be attributed to a change in the character of the horizontal currents, with, probably, increased speeds in intermediate levels.

* See M.O.M. 402 and 402a, " Monthly Meteorological Charts of the Atlantic Ocean ", published by the Meteorological Office, London.

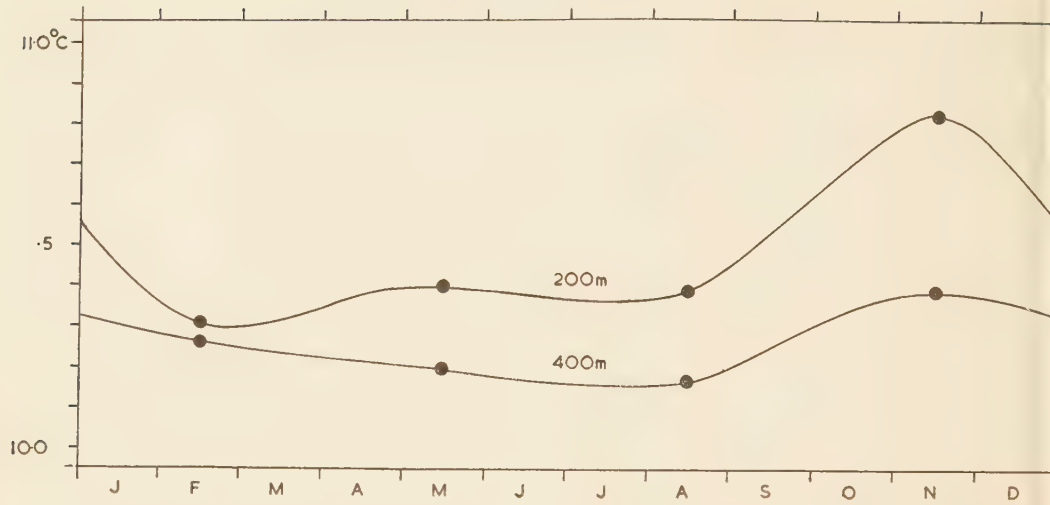


FIG. 8. Average seasonal variation of temperature at 200 and 400 m. over the period 1905-19 in the area 50°-52°N., 10°-14°W. (part of Marsden Square 182).

In this connexion it may be remarked that the data examined in preparing Table suggest the occurrence in more recent years of a notable change in the general temperatu conditions in the intermediate levels. In Fig. 9 the departure of the 200 m. temperatur from the monthly means estimated for the years 1905-1914 are plotted by years (all yea being considered). From this it is evident that until about 1927 temperature conditio at 200 m. remained more or less stationary, but that after that time an increase took plac which, so far as may be judged from the somewhat scanty observations, has in recent yea reached an amount of about $\frac{3}{4}$°C. In his recent paper on temperature and salinity at 200 m Fuglister (6) reproduces Wüst's earlier chart, published in 1936, alongside his own. can be seen that the 11° and 12°C. isotherms extend a good deal further northward in th neighbourhood of Marsden Square 182 in Fuglister's than in Wüst's chart.

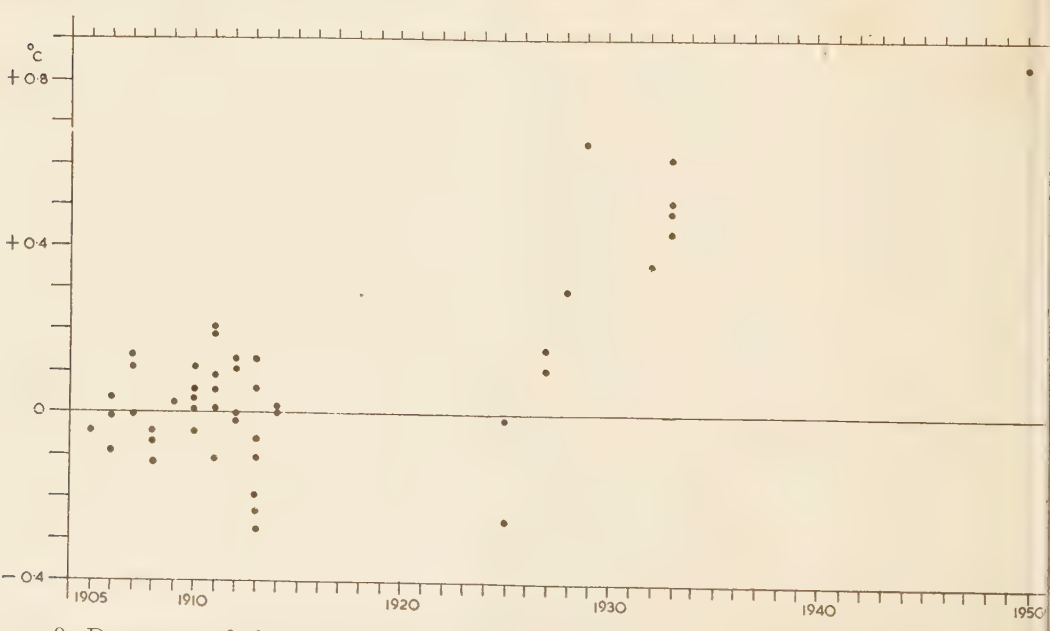


FIG. 9. Departure of the temperature at 200 m. in the area 50°-52°N., 10°-14°W. from t 1905-1914 averages, for the period 1905-1950.

In conclusion, it is to be mentioned that the greater part of the work on which this paper is based was done while the writer was serving in the Hydrographic Department of the Admiralty. The paper is published with the concurrence of the Hydrographer of the Navy, but responsibility for the opinions and statements put forward rests solely with the writer. Gratitude is expressed for the kindness of the Meteorological Office in supplying the wind data, and for the great assistance given by the Nautical Almanac Office in carrying out the initial bulk of the computations. The remainder have been undertaken by the Statistical Branch of the Ministry of Agriculture and Fisheries at Lowestoft.

SUMMARY

The depth of the relatively shallow, homogeneous layer that may be produced by the wind in the surface waters of the oceans has been computed by means of Rossby and Montgomery's (1) formula

$$h = K.\text{cosec } L.\ W_0,$$

in which h is the thickness of the homogeneous layer, L is the latitude, and W_0 the wind speed. The values used for the coefficient K are given in Table 1. For W_0, the first and third quartiles of the frequencies of wind speeds observed by ships have been estimated for Marsden Squares between 60°N. and 60°S. latitude, for three-monthly periods. As the first quartiles of the wind speeds are mainly less than Force 4, only the depths relating to the third quartiles have been further considered. These depths have been charted and contoured (Figs. 1-4); the contours are shown dotted for the lowest latitudes, in which the theory is not strictly applicable.

Although factors other than the wind affect the depth of the homogeneous layer, they are usually of secondary importance, relative to the wind. Hence the charted depths may be expected to accord in a broad way with actual conditions.

The charts indicate noteworthy departures from the latitudinal zoning of the contours which would occur if the wind speeds were everywhere the same. In Atlantic equatorial regions, for instance, the computed boundary surface at the foot of the homogeneous layer slopes downwards from east to west, as is known to occur in fact. Between latitudes 30° to 60°, in the Atlantic especially, the diminution of the effect of the wind with increase of latitude is more than balanced by increase in wind strengths, so that after a rapid shallowing in lower latitudes, the layer tends to deepen again as latitude increases.

In some localities the computed thickness of the layer differs from the observed. These differences may be attributed to the operation of factors other than the wind, which are normally of minor importance.

It seems that although variations in wind strength may give rise to changes in the thickness of the homogeneous layer in the course of a few days, the layer assumes in general a certain fairly steady thickness, which is presumed to be related to the local wind conditions. Comparison of the computed depths with those determined by examination of temperature and salinity data for two localities, one being the northern North Sea and the other the eastern side of the North Atlantic, shows broad agreement in the seasonal trend of the layer thickness. In winter the surface water layers are unstable and no layer is present in consequence. From about April, when the layer first appears, until June a slight decrease occurs in the thickness of the layer, attributable to the diminution of wind strengths. After June, the layer deepens again, in conformity with the strengthening of the wind. From September onwards, however, the observed increase in thickness in the Atlantic region studied is greater than is to be expected from the computed values. Consideration of the hydrographic conditions prevailing in this locality leads to the conclusion that in autumn advection takes place in the deeper levels. The current system evidently changes in such a way as to increase the turbulence in deeper levels, which leads to a layer thickness in excess of that which would be produced by the wind alone.

In the course of the examination of the hydrographic data for the Atlantic, west of Ireland, evidence has been found that the average temperature at 200 m. depth has risen since about 1927, the increase in recent years apparently reaching an amount of about $\frac{3}{4}$°C.

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